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*Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02420

14. ABSTRACT

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Initial Plasma Testing of the Ion Proportional Surface Emission Cathode

Adrian Wheelock* and David L. Cooke†
Air Force Research Laboratory, Hanscom AFB, MA 01731

Michael W. Geis‡
Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA, 02420

The Ion Proportional Surface Emission Cathode (IProSEC) is a low-brightness cathode technology under development for applications where large areas are available for emission and it is advantageous to avoid the space charge effects associated with bright or intense sources. Space applications include spacecraft charge control and electrodynamic tethers. Surface Emission Cathodes emit electrons by concentrating an electric field between a p-doped insulating substrate and an adjacent metal cathode element. The substrate potential is held positive of the cathode with gate elements. In plasma, the gate is eliminated due to ambient ion flux which maintains the substrate potential near plasma ground. Prototype devices have been tested using a laboratory plasma source achieving sustained and stable operation over a wide bias voltage for a given ion flux. Chip-based sources are compared to carbon nanotube mats. The principle of operation, ion flux proportionality, and prototype performance is discussed.

Nomenclature

B	=	Magnetic Field Strength
D	=	Distance over which potential is applied
e	=	fundamental charge
I	=	Current
J_s, J_{0s}	=	Current density of species s, Thermal Current density of species s
m_s	=	Mass of species s
N	=	Number density
P	=	Perveance
R	=	Beam Radius
T	=	Temperature
v	=	Spacecraft velocity
V	=	Potential
ε_0	=	Permittivity of free space.

I. Introduction

Robust, simple electron emission is an enabling technology for many spacecraft applications including electrodynamic tether propulsion and spacecraft charge control. The electrodynamic tether (EDT)[1,2] is a space vehicle that utilizes the $\vec{\mathbf{I}} \times \vec{\mathbf{B}}$ electromotive force between a current-carrying wire and a magnetic field and the complementary $\vec{\mathbf{v}} \times \vec{\mathbf{B}}$ potential induced in the wire by the relative motion of the spacecraft. Depending on the directions of $\vec{\mathbf{I}}, \vec{\mathbf{B}}$, and $\vec{\mathbf{v}}$, an EDT can provide propulsion to raise or lower the altitude of the spacecraft, rotate the orbital plane, or draw usable electric power, as seen in Figure 1a and Figure 1b. EDT performance depends on electron collection, typically by a positively charged collector, and emission by a cathode. Ion collection is not

* Electronics Engineer, Space Vehicles Directorate, AIAA Member.
† Tech Advisor, Space Vehicles Directorate, AIAA Member.
‡ Staff, non-member.

significant due the greater mass compared to electrons. Since the electron collection is passive, it is the cathode that drives system complexity. Another application for cathode technology is spacecraft charging where satellites can acquire potentials of many kilovolts negative in regions of space where hot plasmas are found, again due to the increased mobility of electrons over heavier ions[5]. One such region is the geo-synchronous belt where most of the world's communication satellites fly. Good design is the best approach to withstanding this potential hazard; however it can still be necessary to control the charging by emitting charged particles, typically electrons.[3]

Most approaches to electron emission for spacecraft potential and current control have used intense or bright sources, such as electron guns or hollow cathode plasma contactors, and brightness is a common figure of merit in cathode development. High brightness, however, presents a space-charge limitation to electron escape. In space based electron beam applications, there are three basic approaches to overcoming space-charge barriers and enabling beam escape from the cathode region: raising the beam velocity to reduce the stream density, employing the ambient plasma for neutralization, and emitting a neutralizing flux of ions. The first two approaches are usually found combined in most space based electron beam experiments. To escape the payload vicinity, a relatively high beam energy is chosen such that the beam density will be low or comparable to the ambient density, and the beam current must not exceed the ambient plasma's ability to neutralize charge buildup on the spacecraft via a return electron current. When the return current is exceeded, the vehicle charges positive, decreasing the beam energy and enhancing the beam density until space charge effects return the fraction of beam current required for current closure at the spacecraft. The physics of this complex interaction is discussed in detail by Pritchett[4] and references therein.

The third approach emits not just electrons, but plasma. The plasma ions maintain quasineutrality near the source until the electrons have dispersed sufficiently that the ambient environment provides neutralization. This type of device is generally known as a plasma contactor and is often a hollow cathode[5]. Although very effective, these sources are somewhat complex and require power and gas to ionize for the plasma ions.

With the limitations discussed above, it would seem a good approach to distribute the electron current over a large enough area to reduce the space charge to where it can be neutralized by the ambient plasma ions. In addition, we would desire this ideal cathode to be completely passive with a single wire interface to the system, and for tether application be just a wire with the property of emitting electrons when biased negative in a plasma. The IproSEC may be that ideal cathode.

II. 2 - The Surface Emission Cathode

The Surface Emission Cathode, SEC, has recently been described by Geis et. al.[6] Surface emission cathodes,[7,8,9,10] first reported by Dittmer in 1972[7], consist of two electrodes placed on an insulating substrate. When sufficient bias voltage is placed across these electrodes, electrons are emitted into vacuum. The ratio of the emitted current to the current flowing between the electrodes, the cathode efficiency, was low, $10^{-4} - 10^{-2}$. By replacing the Pyrex glass used by Dittmer with a negative-electron-affinity (NEA) glass, $Cs_2\ Si_4\ O_9$,[11] and using a new electrode geometry, seen in Figure 2, efficiencies greater than 10^3 have been obtained. The NEA property can allow electrons

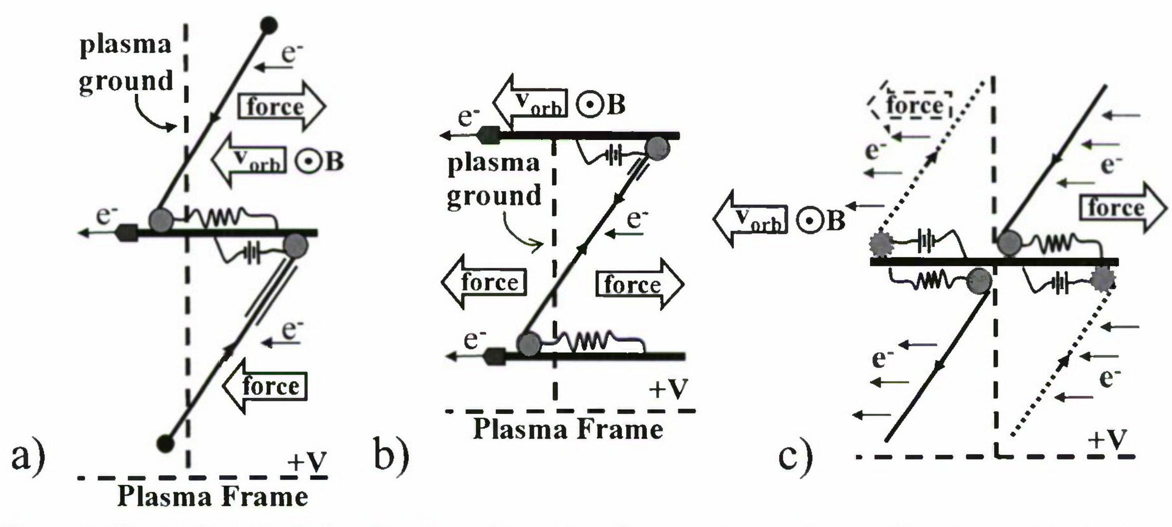

Figure 1: Electrodynamic Tether Configurations: a) emitter on spacecraft only, b) emitter on two spacecraft connected by EDT, c) IProSEC enabled tethers with load (solid) or potential source (dashed)

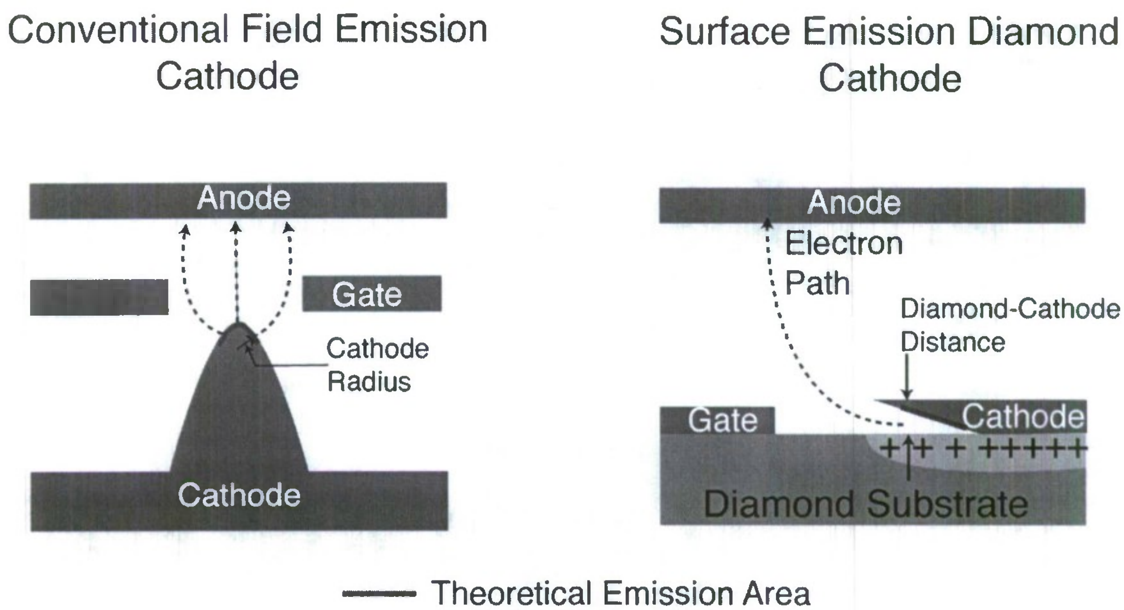

Figure 2: (left) Conventional geometric-field-enhancement cathode with the cathode electrode consisting of an atomically sharp tip from which electrons are emitted. (right) Triple junction surface-emission cathode, SEC, with the gate and cathode electrodes on the same substrate. Positive substrate space charge enhances the electric field at the cathode electrode. Emission area is highlighted in red.

to float on the surface of the insulator without being absorbed into the bulk.[6]

A typical SEC configuration involves two symmetric inter-digitated planar comb-like arrays of fingers perhaps 10 microns wide with a few micros separation between the alternating array fingers. One array functions as a gate and is biased positive with respect to the cathode array which is in turn biased negative with respect to an anode element held above the assembly. A gate to cathode bias voltage of about 200 V is typically needed to initiate emission, which will continue even if the gate is allowed to float, as long as few 10's of Volts of anode to cathode potential is maintained. When the gate and anode currents are both monitored, the ratio of anode to gate current is called the gain, and gains greater than 10^3 have been observed[6].

To understand the cathode physics between the electrode and the glass surface, its properties are summarized; emission requires undercut electrodes and a Cs-glass layer, emission increases with substrate bias, 0 V bias emission occurs at exceptionally low anode fields, but saturates at higher fields. Geis[6] argues that Fowler-Nordheim field emission theory cannot explain these results, and offers an alternative explanation in which electrons tunnel from the cathode onto the glass surface and from there into vacuum. The undercut electrode catalyzes the tunneling of electrons out of the metal onto the glass. As electrons leave a metal surface, their image charge in the electrode reduces the tunneling barrier. This effect is small and is usually ignored, but if the electrons are tunneling between two surfaces separated by vacuum gap of <10 nm, the image charges in both surfaces can substantially lower the tunneling barrier.[11,12] The gap for these experiments is initially 70 nm. However, electrostatic forces are expected to cause the under cut section to adhere to the glass forming regions with gaps of a few nanometers. The NEA property is critical both keeping the majority of the tunneling electrons mobile on the glass surface and away from the trapped positive charge in the glass.

III. The Ion Proportional Surface Emission Cathode (IProSEC)

The IProSEC is a variation on the SEC where the gate element is removed and that function is replaced by plasma ions. Attracted to the cathode, some ions will miss, striking the glass surface and help maintain its positive charge with respect to the cathode. This process is one explanation for SEC emission with the gate floating. The IProSEC thus offers the possibility of a single-wire cathode that will automatically emit electrons when biased negative in a plasma. It is difficult to predict theoretically the current-voltage characteristics of the device in general, but we report here substantial emission at a less than 200 volt bias.

While the chip-based format may provide a greater gain, the field enhancement between a conductor and a dielectric can be exploited in other formats. We also explored using a carbon nanotube (CNT) mat as an emission surface. Two candidates were tested, one 100% CNT and one with a 10% by weight glass fiber component. CNT

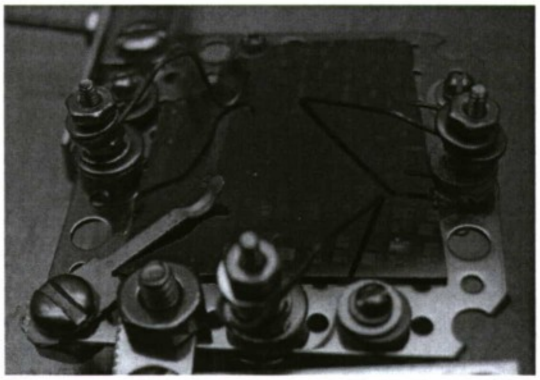

Figure 3: Chip test fixture. Note the multiple IProSEC device pads on a single chip.

mats are constructed using vacuum filtration with water as a solvent and using a standard cellulose filter medium. This results in a large-area sheet of carbon nanotubes with random orientations, potentially interspersed with glass fibers

The pure CNT mat was used as a control to ensure that any electron emission seen was due to dielectric-conductor proximity and not simply due to the conductivity and field-enhancement possible with CNTs.

A potential difficulty with CNT-based IProSEC devices is that in low earth orbit (LEO), there is sufficient atomic oxygen to rapidly react with the carbon, thus rendering it useless for charge control or tether current control in LEO. Geosynchronous orbits could potentially use any CNT-based IProSEC devices as the oxygen and ambient plasma densities are low enough that the device could have a useful lifespan.

IV. Experimental Setup

The experiments in this paper were simply confirmation that the single-wire surface emission would work in a plasma environment. The devices are generated on wafers in bulk and each chip has multiple IProSEC pads on it. The devices were clipped to a stainless steel plate and tungsten leads were touched to connector pads on the devices and output leads. This was placed about ½ inch behind a stainless steel screen which could be independently biased, and everything was about ¼ inch behind a much larger stainless steel plate with a 30 mm screened entrance aperture held at ground potential. The sides and back of the apparatus were shielded from the plasma by a light aluminum shield so that charged particle access was allowed only through the screened aperture. A picture of the chip test fixture is provided in Figure 3. For a control, a stainless steel plate was used behind the grid in a similar enclosure. CNT samples were placed 0.1 inch behind the biased screen which was 0.1 inch behind the large plate. They were also surrounded by the same aluminum shield.

Argon plasma was generated by an Electric Propulsion Laboratory, Inc. hollow cathode aimed at the device. Initial experiments used a distance of about 16 inches. This was increased for the August experiment series to 32 inches in order to reduce the ion flux. Experiments were conducted in the Jumbo space simulation chamber at Hanscom AFB. The chamber has an ultimate pressure in the low 10^{-7} Torr range, with the gas flow from the cathodes the experiments were conducted at high 10^{-6} Torr. The chamber can use both a turbomolecular pump and a cryopump to achieve high-vacuum conditions, with the turbopump utilized in these experiments.

Currents were measured using a Kiethley 237 High-Voltage Source-Measure Unit (SMU). In the first experiments, one unit was used and only the current to the device was measured. With later devices, a second unit was added to control the bias offset of the grid to the device and the current to the grid was also measured. Cables inside and outside were coaxial, with grounded shields. A conversion to triaxial cables for use in the SMUs was made with the middle conductor grounded to the shield.

V. Results

The first results from March 2006 can be seen in Figure 4. An initial sweep without plasma shows no emission other than background noise. The plasma source was activated, and the first sweep clearly shows significant emission. However, after a brief pause, the second and subsequent sweeps show no emission. Subsequent tests also failed to "relight" the device. Another pad on the same chip was tested, and it burned out rapidly as well. The peak current observed of about 3 μA was delivered from a device of approximately 1 mm^2, with the emission area

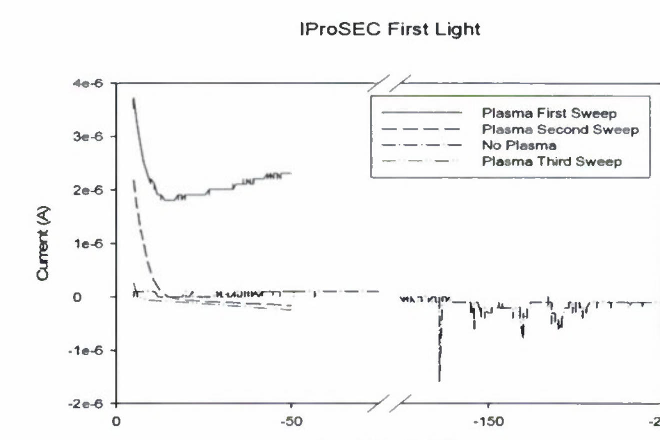

Figure 4: First IProSEC test, sweeps 1-3 with plasma and no plasma. Positive current indicates emission.

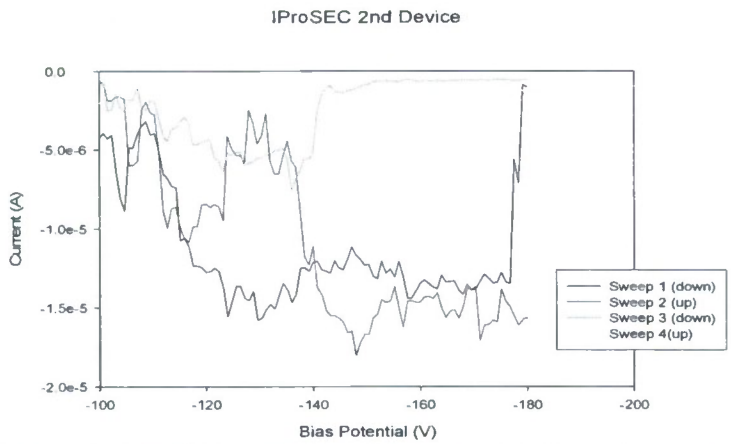

Figure 5: IProSEC sample 2, pad 1, sweeps 1-4. Negative current indicates electron emission

being along the edges of the comb. Although these devices did not last long, we are confident electron emission was observed because the enclosure biasing guaranteed ions of a constant flux would be the only external charged particles allowed in the measurement. Further, the stainless steel control sample measured only the constant ion flux.

A second round of tests was performed in June 2006. Results from the second device can be seen in Figure 5. "Up" and "Down" labels indicate the direction of the sweep, from low negative potential to high negative potential, or high to low. Sweeps in both directions illustrate the ability of the device to remain active even when the potential falls below the initial activation potential.

Another chip was delivered in August 2006 with larger comb areas and larger pads in general. This is the device pictured in Figure 3. The test mount was placed farther from the hollow cathode to reduce the ion flux. The pads were of a variety of sizes, from about 1 to perhaps 5 mm in perimeter with the larger ones giving more surface area for better thermal properties to avoid melting the emission points. Because this chip was reused from another test configuration, it was difficult to determine the actual size of the active pads. Thus the results are not as quantitative as we would desire, but never the less demonstrate electron emission. Additionally, the screen in front of the devices was now independently biased, allowing for independent control of the electric fields seen by the electrons as well as giving a method for measuring emitted current.

As shown in Figure 6, the second set of chips had little to no sign of degradation over the duration of the experiment. Sustained emission of 4 μA was observed from a larger pad, and sustained emission of 150-250 nA was observed from a smaller pad. The screen was biased separately to minimize the effects of the relative size of the device compared to the plasma parameters. By simulating a larger or smaller sheath, emission characteristics should change. There was not a significant difference in the emitted current at either +/- 20V.

In May 2008, a pair of CNT mats was tested at a distance of 31 inches from the plasma source in an attempt to discover the ability of alternate dielectric/conductor configurations to emit under similar situations. A pure CNT mat was tested and the results are visible in Figure 7. There was little to no emission until a short developed between the CNT mat and the electric field screen. When examined later, there was no visible short and no electrical connection after being removed from vacuum, so it is assumed that one or more CNTs were driven across the gap to create the short.

A CNT mat with 10% by weight glass fiber was also tested to introduce a dielectric component. The results are visible in Figure 8 and Figure 9. Emission is comparable to the highest emission of the chip-based devices when the electric field grid has a strong positive bias to the mat. Reversal of the bias between the screen and the mat quenched emission, showing only the ion current. Also included in Figure 9 is a plot showing a stainless steel plate swept in the same manner as the samples. This shows the saturation ion current to the devices as approximately 2e-7 A.

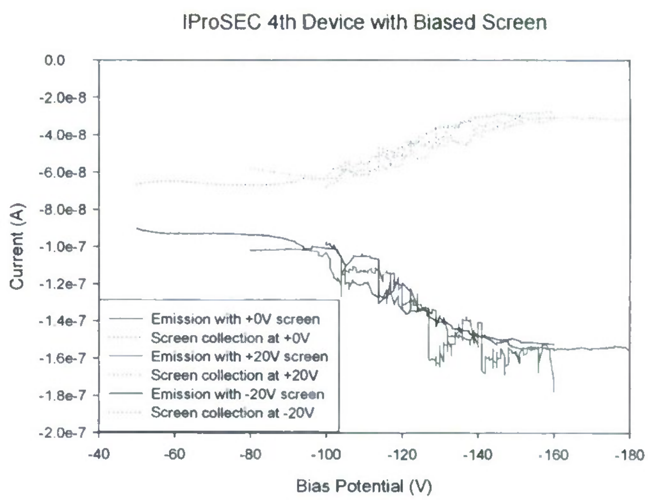

Figure 6: Fourth IProSEC Device. Screen biased at +0, -20V and +20V compared to pad bias. Note screen current in this case.

VI. Discussion

Emission from the device is clear, with a sharp activation point, and emission continues even after the potential is reduced, as expected. While the currents emitted from the devices are small, it is comparable with the typical charging currents to a satellite in geosynchronous orbit of microamps to milliamps per square meter. As these currents were emitted from a device on the order of a square millimeter, it may be possible to counteract negative charging over a large spacecraft with only a small area of IProSEC devices.

The short lifespan of the devices is a significant limitation at this stage. While the devices used in the third round of testing did not show significant degradation over the tests, the rapid burnout of the first test devices suggests that it is possible to over-emit, potentially melting the emission point until the geometry has changed sufficiently to bring the electric fields below the threshold needed for field emission. This happens in stages as individual emission points fail. This suggests that the thin comb design may not be optimal. Designs that can better conduct heat away from emission points would be superior to the present devices. The rapid burnout also suggests that despite the large potential emission area on the pads, emission is primarily from only a handful of locations.

In the third round of testing, with the screen biased as well, there is a conspicuous lack of electron current impacting on the screens in the first set of August tests. Despite a reasonably high transmissibility, it is unlikely that the current to the screens was below the noise threshold on the SMUs. A possible explanation for this could be that the current was flowing to other pads on the chip that had not been biased and thus were charging positive under ion bombardment. Alternately, it could be emitted to a grounded point on the test stand apparatus. The fourth device tested, which did show emission to the screen, was likely due to the pad under test having a geometry where the electrons would not be drawn to other pads or the test structure.

The CNT mat with fiberglass shows comparable emission to the chip-based devices. However, as there are no surfaces inside the sample holder to collect the current other than the field screen, little of the emission is collected by the screen, so emission is to the plasma environment in the chamber. The distinction between the fiberglass and pure CNT mats illustrates the ability of dielectric charging to enable field emission at plasma-dielectric-conductor triple-point junctions.

The stainless steel plate serves as a control since both the plate and mats are illuminated by ions passing through identical apertures, making it possible to determine the gain of the sample. It can be seen in Figure 8 and Figure 9 that the device is producing a gain of approximately 10 with a screen bias of +20V, and over 100 with a screen bias of +70V. Gains of this level are sufficient to enable current control of electrodynamic tethers as explained below.

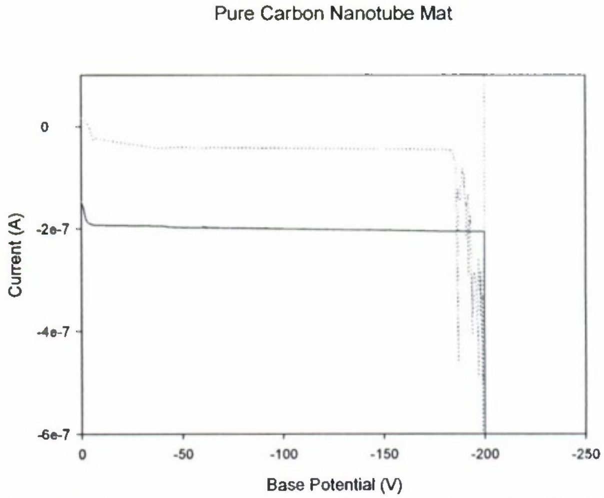

Figure 7: Pure CNT mat. At approximately -200V a short developed and current went to instrument current limit. Screen is dotted line.

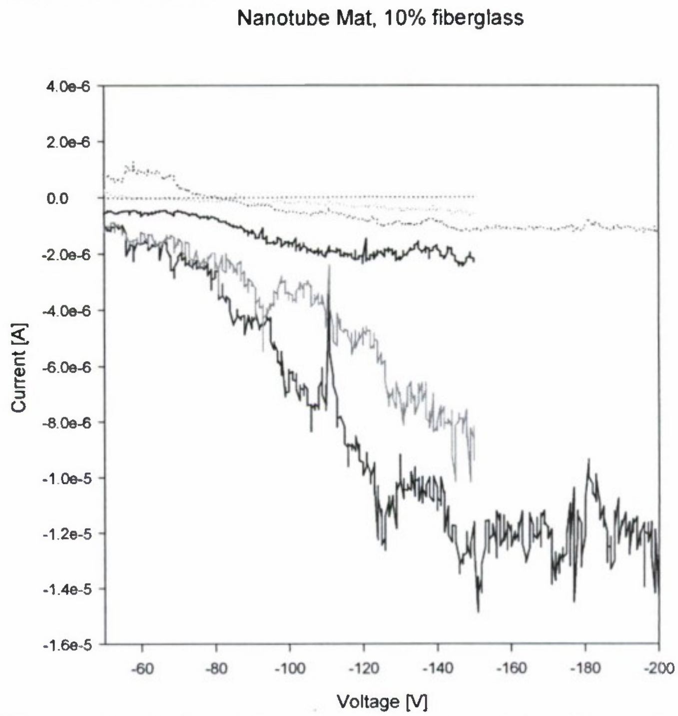

Figure 8: Carbon Nanotube Mat with 10% fiberglass content. Screens (dotted) biased from mat by +10V (blue), +50V (green), and +70V (red)

VII. Electrodynamic Tethers and Other Applications

Electrodynamic tethers utilize the $\vec{\mathbf{I}} \times \vec{\mathbf{B}}$ force on a current-carrying wire and a magnetic field. Depending on the direction of the current, this can produce either a drag or a thrust. Tether performance is dependent on electron collection and emission, as ion collection current is generally 1/200 to 1/50 the electron collection current. The TSS-1, TSS-1R[12], and ProSEDS[13] missions used a current collecting tether extended above the spacecraft with electron emission on the spacecraft, as seen in the top half of Figure 1a. The Plasma Motor Generator (PMG) mission[14] expanded the utility by using two satellites, each with an electron emitter, connected by a tether. This allowed one satellite to act as collector and the other as emitter, giving both push and pull maneuvers as seen in Figure 1b. The PMG emitters were plasma contactors, making the useful lifetime of the tether dependent on the propellant supply.

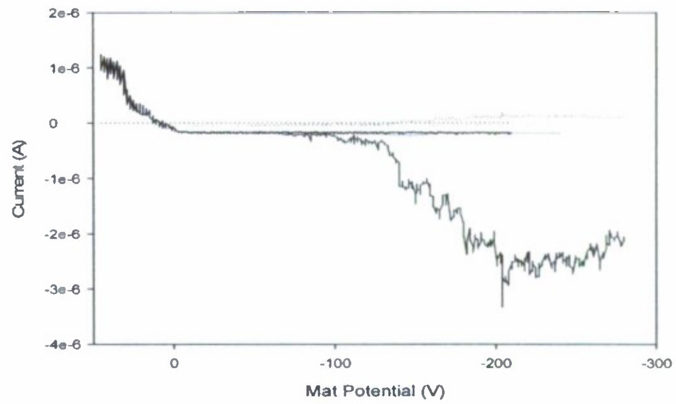

Figure 9: Carbon Nanotube Mat with 10% fiberglass content, with screen (dotted) positive 20V to mat (red) and screen negative 20V to mat (green). Stainless Steel Plate for reference in black.

Greater utility would come out of electrodynamic tethers if the current could be easily reversed, without requiring propellant for plasma contactors – if electrons could be emitted as easily as collected. A single tether could be both a push and a pull option simply by switching the tether connection between a battery and a load. The IProSEC enables the emission of electrons anywhere in the system, creating a one-tether, one-wire propellant-less propulsion system, giving the options seen in Figure 1c. Using a push-pull EDT allows maneuvers previously unattainable due to their high delta-V cost, such as unlimited reboost capability or 180-degree polar orbit plane changes.

VIII. Conclusions

The IProSEC device is potentially an enabling technology for Electrodynamic Tether missions. This will be particularly true if IProSEC properties can be built into the same material that is used for electron collection, be it a thin wire or an end collector. Using such an emitter-collector approach, an EDT could deploy identical tethers up and down from a central body. Each tether would be capable of collecting or emitted electrons making motor and generator modes equally accessible. Using more conventional cathodes that require control, an EDT mission requiring both motor and generator modes would need two active end satellites each fitted with cathodes and possibly tankage as well.

For applications outside of LEO, the CNT pads could provide passive spacecraft charging control and potentially even the neutralization of ion propulsion engines where the cathode would be positioned to intersect off-axis charge exchange plume ions and return neutralizing electrons. However, carbon nanotube mats are ill-suited for tether applications in LEO due to the atomic oxygen that dominates the environment at those altitudes. The mats would react with the oxygen and be destroyed in short order.

Initial results demonstrate one-wire surface emission in a plasma environment, but also highlight the need for a more robust design. Emission of up to 30 µA was observed, with sustained emission of 4 µA at a lower ion flux. Electron emission appears to come from individual points, which may "burn out," leaving less-powerful emission sites as evidenced by the drop in emission current over several voltage sweeps. Improvements in thermal conduction away from emission points are likely needed to enhance device lifespan. Emission geometry may explain the initial lack of electron current to the biased grid

Appendix: Space Charge Analysis

It appears that electron emission over a large area rather than a discrete location is a potential solution to the limitations in other cathode technologies with regards to EDTs. In a single dimension, the current that can be drawn even from an infinite source of charged particles is dependent on a specific voltage. This is the well-known Child-Langmuir Law[15,16] given by

$$J_s = \frac{4\varepsilon_0}{9}\left(\frac{2e}{m_s}\right)^{\frac{1}{2}}\frac{V^{\frac{3}{2}}}{D^2}. \tag{1}$$

Here, J_s is the current density of species s, m_s is the mass, V is the potential difference driving the current, and D is the distance the voltage is applied over. Perveance, a property of charged particle beams of radius R, can be defined from this as

$$P = \frac{I}{V^{3/2}} = \frac{4\pi\varepsilon_0}{9}\left(\frac{2e}{m_s}\right)^{\frac{1}{2}}\left(\frac{R}{D}\right)^2 \cong 2.33\text{x}10^{-6}\pi\left(\frac{R}{D}\right)^2. \tag{2}$$

By considering this relation with a time reversed view from the anode, we see that an electron beam of current density J, and energy eV, can traverse a gap no greater than D without forming a virtual cathode or stagnation point that will return some or all of the flux.[17] There is a strong dimensional aspect to perveance and our intuition tells us correctly that a beam can expand into 2 or 3 dimensions with much greater perveance or less concern for stagnation. A fully developed electron emission system requires specific and usually numerical design, however we may still characterize the transition from 1D (the cathode surface) to 2 or 3 dimensions with the following simple principle. *If an electron beam has a current high enough to stagnate in a distance small compared to the characteristic dimensions of the emitting surface, the advantage of a later expansion is never realized.* Thus we may illustrate a perveance limit by setting $R/D = 3$ so that, $I \le 6.6\text{x}10^{-5}V^{3/2}$ where we may interpret V as the energy of the electron beam. So we see that if a spacecraft desires to emit say, 100 mA of current, beam energy of approximately 125 Volts will be required to avoid stagnation. Of course an extraction grid can be placed close over the cathode surface so that $D << R$ thus increasing the perveance, but the stagnation will simply appear just beyond the extraction grid unless further extraction is provided to maintain the perveance and ultimately form a beam with reduced density.

Any beam voltage is a parasitic loss and is undesirable for a tether system. If the tether is used solely for de-orbiting a spacecraft and the objective is to dissipate energy, the high cathode voltage is mostly a nuisance. If however, the tether system is used for propulsion or to extract useable energy from the orbit, the beam power is lost which for the above example is about 12 Watts. The advantage of the SEC comes from recognizing that when the SEC is distributed over a large enough surface, D scales larger as well and at some point becomes irrelevant compared to other scale lengths.

To determine the necessary gain an IProSEC device would need to reach the space charge limit, we consider a long, thin cylinder. If the radius is small compared to the plasma Debye length, current collection is not space charge limited and is instead governed by Orbit Motion Limited theory.[18] OML current collection is given by

$$J_s = J_{os}\left(2/\pi^{1/2}\right)\left(eV/kT_s\right)^{1/2} \\ eV/kT_s > 3 \tag{3}$$

$$J_{os} = Ne\sqrt{kT_s/2\pi m_s}\,. \tag{4}$$

where J_0 is the ambient thermal current for species s, N is the number density, e is the electron charge, k is Boltzmann's constant, and T is temperature. As (4) holds for both ions and electrons, we see that the ratio of ion to electron current is

$$J_e/J_i = \sqrt{T_e m_i/T_i m_e}\,. \tag{5}$$

This means that the electron flux will exceed the ion flux by a factor of 50 to 200 or more. For an oxygen plasma, the ratio is 171. Current balance between positive and negative potential collecting areas would require the area dedicated to ion collection to exceed that for electron collection by a factor of about 171. If, however, the ion collection surface can emit electrons in proportion to the incoming ions, a cathode gain of only 171 is required to achieve current balance with equal areas. Higher gains will allow even further reduction in the cathode area until the space charge limit is reached.

Analysis of the space charge limit is specific to the cylinder radius and the plasma parameters and must in general be evaluated numerically. We may however, make considerable progress by considering certain facts about space charge limited systems. First we observe that in a parallel plate system consisting of an emitting cathode and anode, the ion and electron fluxes behave as described in Equation (5). This arrangement is called a double layer, and the perveance relationship is similar to Equation (1) with D increased by a factor of 1.36, or the current densities increased by 1.86.[19] Furthermore, the work of Langmuir and Blodgett[19] and Wei and Wilber[20] demonstrate that in concentric 2 and 3 dimensional configurations, the outgoing space charge limited flux can exceed the incoming flux by a factor of 2 or more. It is therefore very conservative to apply both these factors to the less dense OML collection and predict reductions in either the required cathodic area or Voltage, and that IProSEC cathode gains of 200 to 1000 can easily be employed in passive collection configurations. Higher gains will at some point approach the actual space charge limits, but the inherent robustness of the IProSEC means that this does not impose any liability.

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